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Economics of Nuclear Gas Stimulation

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ECONOMICS OF NUCLEAR GAS STIMULATION

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ABSTRACT

Nuclear stimulation of the Mesaverde Formation in the Piceance Basin appears to be the only available method that can release the contained gas economically. In the Rulison Field alone estimates show six to eight trillion cubic feet of gas may be made available by nuclear means, and possibly one hundred trillion cubic feet could be released in the Piceance Basin.

Several problems remain to be solved before this tremendous gas reserve can be tapped. Among these are (1) rates of production following nuclear stimulation; (2) costs of nuclear stimulation; (3) radioactivity of the chimney gas; and (4) development of the ideal type of device to carry out the stimulations. Each of these problems is discussed in detail with possible solutions suggested.

First and foremost is the rate at which gas can be delivered following nuclear stimulation. Calculations have been made for expected production behavior following a 5-kiloton device and a 40-kiloton device with different permeabilities. These are shown, along with conventional production history. The calculations show that rates of production will be sufficient if costs can be controlled. Costs of nuclear stimulation must be drastically reduced for a commercial process. Project Rulison will cost approximately \$3.7 million, excluding lease costs, preliminary tests, and well costs. At such prices, nothing can possibly be commercial; however, these costs can come down in a logical step-wise fashion.

Radiation contamination of the gas remains a problem. Three possible solutions to this problem are included.

INTRODUCTION

The greatest challenge to the oil industry has always been how to make available oil and gas at an economic rate. The increasing costs of exploration havemade the economic development of marginal resources not only attractive, but necessary.

Over the years, the development of stimulation methods have made it possible to produce from reservoirs which earlier would have been written off as dry holes. Among the first successful methods was the use of the chemical explosive (nitroglycerine) to break up the area immediately surrounding the well bore. Later, another method still in common use in limestone reservoirs, was acidizing to open up flow channels in the rock further out into the reservoir. These two stimulation methods have now been dwarfed by hydraulic fracturing,(1) the most commonly used technique available to the industry today. The object of fracturing is to increase the flow from the reservoir by increasing the flow capacity of the rock close to the well bore. It works extremely well in thin formations where the entry point of fracturing fluid can be controlled.

Stimulation is more difficult when thick, tight formations are the targets. This is because it is hard to force the fractures into the desired zones of the formation and connect up all of the sand lenses with the well bore. The introduction of nuclear fracturing (2), (3) should solve the thick formation stimulation problem. Massive fractures are created by the nuclear explosive which cross the sand and shale sequences of such thick, tight formations. Use of nuclear stimulation should allow economic production from zones which are non-commercial by ordinary stimulation methods.

EFFECT OF NUCLEAR EXPLOSIVES

Numerous other papers at this symposium have discussed nuclear explosions and their effects on various rock types. In review, a completely contained explosion creates a chimney and fractured rock zone much like the ones shown in Figure 1. (4), (5) The size of the chimney and fractured zone varies with the size of device or amount of energy used. Let's look briefly at how these huge rock piles can be used to increase gas production.

Under normal situations a hole is drilled into the gas formation and 5-1/2 inch or 7-inch casing is cemented in place. Gas flow is initiated into the well bore by perforating and then reducing the pressure in the well bore. As the gas moves from the higher pressure in the reservoir into the well, it flows through the area immediately surrounding the well (See Figure 2). There is a restriction to flow due to the limited area through which the fluid can pass. The rate at which the gas can be produced is a function of the permeability of the reservoir and the available flow areas.

When a nuclear device is exploded in a reservoir, it yields the configuration as shown in the bottom half of Figure 2. (6) Superimposed on the well bore is a highly fractured area surrounding a rubble of broken rock. The gas flows toward these fractures from the tighter or less permeable original reservoir. The flow rate into such a well will be a function of the size of the broken up area and the formation permeability. In other words, the larger the area of fractures, the faster the flow rate into the new well. If the nuclear stimulated well rates are much greater than the original unfractured rates, it will be economic to use nuclear explosives and fewer wells should be required to drain the reservoir.

Two nuclear gas stimulation experiments have been carried out--Projects Gasbuggy [7] and Rulison. [8] The objective in both cases was to open up a tight formation and allow a higher rate of production. Preliminary results are in on Gasbuggy and are discussed by others at this symposium. A re-entry is planned for Rulison in April of this year.

RULISON RESULTS

The paper by Reynolds et al [9] presents much of the pre-shot test data from Rulison. Using the mathematical model discussed there we have calculated a series of curves showing the effect of shot size and permeability on the predicted performance of a gas reservoir. These calculations should allow us to zero in on the economic future of nuclear stimulation and the limits of usefulness of the method.

Figure 3 gives our pre-shot predictions on recovery from the Rulison test. The measured reservoir permeability was 0.008 md. Using a 40-kiloton device, we should obtain a 7-fold increase over normal production in 20 years. Obviously, the experimental shot is not predicted to pay for itself since only 6 billion cubic feet of gas is expected in 20 years.

Using the same model, Figure 4 was made. It shows the effect of variation in permeability on recovery predicted in 20 years using a 40-kiloton device. As expected, recoveries are much higher with an increase in permeability. At very low permeability, gas recovery following nuclear stimulation will be too low to make the method economic.

Figure 5 is the same plot using a 5-kiloton device. In this kind of application it would be assumed that a sufficient number of small devices would be used in one well bore to break across the entire production interval. Thus, the results are comparable to those of Figure 4 for the 40-kiloton device. It is apparent that a 5-kiloton device needs a much higher permeability to recover a substantial amount of the gas-in-place in 20 years.

Figures 6 through 8 show the comparison of recovery from 5- and 40-kiloton devices as a function of permeability. These data show that larger size devices become more desirable as the reservoir permeability decreases. The device yield selected will be governed by the seismic effects as well as the economics of recovering the gas-in-place.

In Figure 9, we have attempted to summarize the data by plotting 20-year recoveries versus permeability as a function of shot size. It is readily seen that 20-year recoveries fall off rapidly as the permeability decreases. This means there will be a limiting permeability below which even the tremendous power of the nuclear explosion will not yield production rates that are economic.

Comparison of the data in Figures 3 and 9 lets us draw some interesting conclusions about the type of gas reservoirs applicable to economic stimulation. With higher permeability reservoirs, we can use small devices in series and still obtain high recoveries. If the permeability is low, less than 0.01 md for example, we will be forced to use larger devices in order to obtain adequate production and recovery rates. If the permeability approaches 0.002 md, probably even large devices (100 kt or so) cannot be economically used unless we have tremendous quantities of gas-in-place.

At higher permeabilities (above 0.03 md) it may well be possible to increase the spacing to 640 acres. This would be especially attractive if larger devices (50 kt or more) could be used in the area without seismic damage.

After this analysis one is tempted to ask how good is it? Of course, it can be no better than the assumptions on which the reservoir model is constructed. First indications from Rulison are that the model may be somewhat conservative. We hope this statement is borne out by our Rulison test program since that would mean smaller devices than originally planned can be used.

Figure 10 gives the pressure buildup in the Rulison emplacement hole. By 30 days (720 hours) surface pressure was 2300 psi (approximately 2700 psi bottomhole) which is within less than 250 psi of original reservoir pressure of 2930 psi. It is interesting to speculate on what is happening and the gas flow rates across the fractured zone into the nuclear chimney.

Seismic measurements indicate that the device behaved as predicted (40 kt $^{+20}_{-4}$). Therefore, we would expect the cavity configuration to be in the range given in Table I. Gas accumulation in the chimney at the original reservoir pressure (2930 psi) might vary between 200 to 700 million standard cubic feet. We won't know which number is correct until the cavity is entered and its size determined.

Predicted chimney void space varies from 1.5 to 5 million cubic feet. This void volume comes from squeezing the rock in the vicinity of the shot and the vaporizing and resolidifying of the rock in the immediate area of the blast. If we assume the squeezing process takes place evenly on the sand grains and shale with no effect on the sand porosity, all of the void space will be newly created by the shot. (In actual fact, part of the new volume would come from squeezing the original porosity and thus all of the void space is not newly made. Since porosity is only 9.7% and sand is only about 40% of total rock, this assumption probably isn't too bad.)

If we consider the minimum fracturing case and consult Table I, we see that the total fractured zone void space (4.5 x 10^6 cubic feet) is only 3 times the chimney void space created by the device. Total gas in the fractured area should be about 900 MMSCF. If no flow occurred from the unfractured portion of the reservoir across the fractured boundary, the gas pressure in the well bore after 30 days of buildup should not be above 3/4 of the original pressure or 2200 psi. Since the observed pressure is approximately 2700 psi, the increase in pressure of 500 psi over a non-flow situation will give a measure of the gas flow rate across the fracture boundary.

TABLE I

PREDICTED CAVITY PROPERTIES FROM RULISON EXPLOSION [10]

	Maximum	Mean	Minimum	Units
Cavity Radius	108	90	72	feet
Cracking Radius	580	485	390	feet
Chimney Height	451	376	301	feet
Chimney Volume (Broken rock)	$1.65x10^7$	$9.57x10^6$	$4.90x10^6$	$feet^3$
Cavity Volume (or Chimney Void Space)	$5.28x10^6$	$3.05x10^6$	$1.56x10^6$	$feet^3$
Gas in Place @ 2930 psi 375^o F (in Chimney)	$721x10^6$	$417x10^6$	$214x10^6$	$feet^3$
Fracture Zone Volume (Fractured rock)	$854x10^6$	----	$256x10^6$	$feet^3$
Fracture Zone Void Space	$15.3x10^6$	----	$4.5x10^6$	$feet^3$

$$\text{Gas Flow/30 days} = \left(\frac{\text{Fractured zone}}{\text{void space}} + \frac{\text{Cavity}}{\text{volume}}\right) \times \frac{\text{Observed pressure increase}}{15}$$

$$\text{Gas Flow/30 days} = (4.5 \times 10^6 + 1.5 \times 10^6) \times \frac{500}{15}$$

$$\text{Gas Flow/day} = 7.5 \text{ MMSCF}$$

This calculation neglects the effect of temperature which will, of course, bring the figure down slightly. It should be pointed out that this flow rate occurs with only a differential pressure of from 730 to 230 psi during the 30-day period.

The results are much higher than expected since the production across the fracture boundary is taking place at such a low differential pressure. Rates should be higher across the boundary during production where the well bore pressure will be held at a much lower value. The actual flow rates and cavity volume will be determined from re-entry and flow testing of the well.

If one uses the maximum case:

$$\text{Gas Flow/30 days} = (15.3 \times 10^6 + 5.3 \times 10^6) \frac{500}{15}$$

$$\text{Gas Flow/30 days} = 20.6 \times 10^6 \times \frac{500}{15}$$

$$\text{Gas Flow/day} = 23 \text{ MMSCF}$$

Both the minimum and maximum flow rates appear quite high and probably indicate a larger fracture area to chimney volume ratio than our model. This would be highly desirable since the expected flow rates and ultimate recovery increase with fracture extent.

If the testing results on Rulison verify the preliminary data, it may be possible to develop the field commercially with smaller shots than originally predicted. This would be an exciting development since safety costs and damages would go down if the explosive yield is reduced.

FUTURE DEVELOPMENT OF NUCLEAR STIMULATION

Production data on Rulison are vital in determining how successful nuclear stimulation will be. If production rates hold up as the pressure buildup indicates, many areas of the western United States will be amenable to economic nuclear stimulation.

In our previous discussion we listed a possible cut-off point of 0.002 md as being attractive by nuclear stimulation. Of course, if the fractures are much longer than those simulated in our model, it may be possible to go to reservoirs of lower permeabilities. The slope of the curve (Figure 9) doesn't give us too much hope of ever going below 0.001 md, however. Here the production rates across the boundary between the virgin reservoir and the fractured zone wouldn't be high enough to make development economic. Of course one could still deplete the fractured area of the reservoir at a high rate, but this doesn't have enough volume (25 acres for 200 kt) in a gas reservoir to be economic. The situation might be different in an oil reservoir where conceivably one could fracture the entire reservoir economically by closely spaced nuclear shots.

Figure 10 shows a map of the areas where nuclear stimulation looks promising. In the Rulison Field alone there is an accumulation of some 8 trillion standard cubic feet. In this entire area there may be several hundred trillion standard cubic feet. The Bureau of Mines estimated 317 trillion cubic feet of gas as recoverable by nuclear means.[11]

Successful economic use of nuclear explosives may well reverse the trend to reduced reserves of natural gas. Figure 11 shows the gas production trend and the years of reserves remaining at current production rates. Gas, which is the cleanest of all fuels, is in short supply and growing more critical. Something must be done to make more gas available to the constantly increasing market.

With the target so large and the technology almost in our grasp it seems strange that so little money has been spent by the AEC on developing nuclear stimulation. Instead they keep pouring hundreds of millions of dollars yearly into development of various types of nuclear power reactors. For only a small fraction of this investment they should be able to develop the proper type of devices to make nuclear stimulation clean, economic, and readily available to utilize our already known gas reserves in tight reservoirs. We can't help but agree completely with Dr. Henry Dunlap's[12] statement that, "It would appear we're either spending too much on reactor development or too little on nuclear stimulation of gas reservoirs." Since our society is constantly clamoring for more non-polluting energy, we advocate vigorous efforts to bring the new technology of nuclear stimulation to rapid commercialization. The U. S. Government has an additional reason for developing nuclear stimulation. Over half of the acreage is Federally owned and direct royalties to the U. S. Government would be large. For example, if the Bureau of Mines figure (317 trillion SCF) is correct, royalty income to the USA could be as high as 4 billion dollars.

PROBLEMS TO SOLVE BEFORE ECONOMIC NUCLEAR STIMULATION

Costs

Foremost among the problems that must be solved is the reduction in cost. The two gas stimulation experiments performed thus far were so expensive they could not possibly be economic. Unless costs can be reduced drastically, the nuclear method can never be made economic.

The cost of a gas stimulation experiment is highly dependent upon the technical objectives and, as such, costs can vary considerably between experiments. Because of this, the Rulison costs should not be thought of as an expected norm for either further experiments or commercial projects but rather as a reference point from which sensible deviations can be made. Rulison is estimated to cost approximately $5.9 million upon completion

(See Table II); however, it is clear that on future events this could be significantly reduced. For instance, Rulison incurred costs of $271K because of a delay. One Hundred Forty-Two Thousand Dollars was incurred because of weather delays imposed by the current procedure which assumes that an accidental release of radiation will occur regardless of the depth of burial. Both of these factors should be eliminated--one by better initial planning, and the other by appropriate implementation of accidental venting safeguards. Experience gained from this event indicates that an additional million dollar-plus reduction could be achieved, even for a similar experimental event.

Table II depicts experimental cost estimates which include actual costs to date plus estimated costs to complete the experiment. The second column indicates what costs should be expected for Shot #6 in the Rulison Field. It is quite evident that significant reductions not only can be, but must be made if we are to achieve economic stimulation.

You will note that well costs are not included in the summary dealing with Shot #6. This is simply because well costs can vary significantly for different areas. For Rulison the well costs will decrease with technological development, possibly by such factors as shooting in an uncased hole, reduction in well diameter and stemming techniques allowing simplified reentry.

At first glance, a total cost of $ 700K for Shot #6, excluding well costs, might appear overly optimistic in view of the experimental costs. However, referring to the chart, Items I, II, and III , totalling almost $2. 1 million do not need to be repeated for operations in the same area. The development of the operational plan and the contract with the Government should become routine with a cost reduction of at least $130K.

Site Preparation, Maintenance, and Logistic Support could easily be reduced $95K even under experimental conditions. A reduction of $460K for explosive services remains a questionable item; however, these costs should be reduced to around $200K under the influence of the Non-Proliferation Treaty and with the development of off-the-shelf explosives.

Explosive Operation, Operational Safety, Seismic Documentation and Damage, Project Management and Public Relations are generally area-wide activities and thus the cost of performing these for five nuclear explosions on the same day would not be significantly greater than that for one. By amortizing these costs over five events, and recognizing that a good portion of these costs is due to the flaring operation, it is easy to envision another reduction of $1. 3 million.

These reductions will not just simply happen as a matter of course; active effort by both industry and Government must be made. Industry will be looking to the Government for such things as reduced device size and costs, stemming techniques (which can only be developed at the Nevada Test Site), appropriate safety criteria and encouragement. Industry is faced with developing efficient operations, technical know-how, and safety capabilities presently associated only with the Atomic Energy Commission.

TABLE II.

RULISON: EXPERIMENTAL VS. PREDICTED COST FOR SHOT #6

	Experiment $K	Shot #6 $K
Feasibility and concept	77	0
Exploratory location (drill well and test)	1089	0
Site characteristics, documentation and reporting	875	10
Develop operational plan and contract with Government	162	20
Site preparation, maintenance, and unallocated logistics	194	100
Emplacement hole	754	*
Explosive services	658	200
Explosive operations	276	140
Operational safety	656	80
Seismic documentation & damage	278	60
Post-shot drilling	230	*
Production	300	50
Project Management	299	30
Public Information	103	10
	5900	700*

* Well costs not included.

Radiation

The second major problem to tackle is radiation. Assuming the cost can be brought down to an economic level we must engineer around the contamination problem.

In gas stimulation, all of the radionuclides are initially contained. The cesium, strontium, and other insoluble silicates will be trapped at the bottom of the cavity. Such solids will not leach into aquifers since they are insoluble and further the flow is always into the nuclear-created well bore, not away from it. The remaining problem then is the radioactive gaseous byproducts.

The type and amounts of gaseous byproducts can be controlled somewhat by choice of the device and explosive environment. Here is an area where the AEC should be hard at work on device design. In the Rulison shot, a fission device was used with a boron carbide shield to cut down generated tritium by a factor of 3 or 4. Other such refinements are possible by the excellent laboratory staffs of LRL and LASL.

In general, we need to be concerned with only two gaseous radionuclides, tritium and krypton. Iodine, though produced in large quantities by a fission device has a short half-life (8 days) and can be allowed to expend itself simply by delayed reentry.

Krypton 85 is a byproduct of the fission or atom bomb. Its concentration can be reduced by using a fusion or H-bomb. However, this increases the concentration of tritium, some of which remains behind unused from a thermonuclear reaction.

The total gaseous radiation expected in Rulison is actually very small; less than 0.3g (3,000 curies) of tritium production (an isotope of hydrogen) was estimated. This would be equivalent to the amount contained in about 1 cc of pure tritiated water. The amount of krypton produced was calculated as 1,000 curies or 0.02 cubic feet of gas at standard conditions.

The problem is caused by the mixing of the radioisotopes in the gas following the detonation. These small amounts of gases are mixed in the 200-700 million standard cubic feet of methane expected in the cavity. As a further complication some of the tritium will partially exchange with hydrogen of the methane to give a small amount of tritiated methane.

Let's look a little further at the tritium problem. Since over 90% of the tritium will stay behind with bound water in the cavity, there will probably be less than 0.03g or 300 curies produced with the gas in the chimney. (For comparison, natural cosmic radiation produces about 6,000 g of tritium per year.) If we assume the gas is burned and mixes in the air above the ground within one mile of the well (a very conservative estimate), we calculate a concentration of tritium in air many times below the allowable tritium in air levels given by the standards set by the Federal Radiation Council. For the layman, if a person breathed this air for one year (which is impossible since the air would mix with other air), he would receive less total radiation than 1/30 the amount he gets from one chest x-ray--or less radiation than the amount he gets from flying from Las Vegas to New York in a jet airplane.

How serious are other gaseous radiation problems? Judging by the sound and fury of the opponents to Rulison, it must appear very dangerous. Actually, however, the total amount of krypton in the cavity at Rulison is also small compared to that encountered every day in our society. The total amount of krypton from Rulison (1,000 curies) is produced in 2-1/2 days operation of a 1000 megawatt nuclear reactor and nuclear power is much cleaner from a radiation standpoint than coal-fired power. [(13), (14)]

It's obvious we have an information gap somewhere and should get busy informing the layman of the facts of radiation. Until we get the message across, we will have a public acceptance problem. Alleviating this problem is extremely important because the public should actually be demanding rapid development of nuclear gas stimulation as a way to obtain energy with minimum pollution.

But facts don't cover emotions and this radiation was created by a bomb. Thus, uncontrolled venting of the gas, though it would be safe, is probably not a good answer to the radiation problem. Further, it would be a terrific waste of energy which our economy can ill afford.

The first solution to the problem might be achieved by mixing. In other words, take the slightly contaminated chimney gas and dilute it several times with non-contaminated gas before it goes into a pipeline. This solution is technically sound but again, because of the emotional aspect, may not be feasible.

A second solution is to pipe the chimney gas out of the basin to a remote area and use it to generate electric power. All that is needed is an ample supply of cooling water and controlled burning so that radiation levels are maintained far below any possible radiation damage. This plan is under study and may well be the best answer.

A third solution is to work out a method of separating the contaminated from non-contaminated gas. This would be quite a technical undertaking since krypton has a boiling range close to that of methane. Further, any tritium which has formed tritiated methane is extremely difficult to separate from non-tritiated methane. But the separation may be possible and research should be done in this area. In other applications such as storage, removal of the radioactive gas would present much less of a problem.

SUMMARY AND CONCLUSIONS

Nuclear gas stimulation is close to economic use. Though the two gas shots Gasbuggy and Rulison have been expensive experiments, we have shown how these costs can be reduced to make nuclear stimulation attractive. Successful development of the method may radically change the gas shortage which is developing in the U. S.

Preliminary results from Rulison are encouraging. Pressure in the cavity has built up rapidly, indicating a high flow rate from the virgin reservoir rock into the fractured zone. If the build-up data is confirmed by long-term flow tests, we'll find that our original predictions were far too conservative. This would mean we can produce the stimulated gas wells at higher rates than expected or reduce the size of device needed to stimulate gas wells economically.

Several problems need further concentrated effort. Costs of the operation must be reduced drastically or it will never be economic. Such reductions can only be achieved through close cooperation between the AEC and industry.

Radiation has emerged as the major problem to be solved. Here the major answer lies in education of the population since nuclear stimulation will allow increased production of gas which is the cleanest power source available. However, other solutions such as device design changes to reduce the actual amounts of radiation, burning chimney gas for generating electricity, and methods of physically separating the krypton and tritium from methane should be studied.

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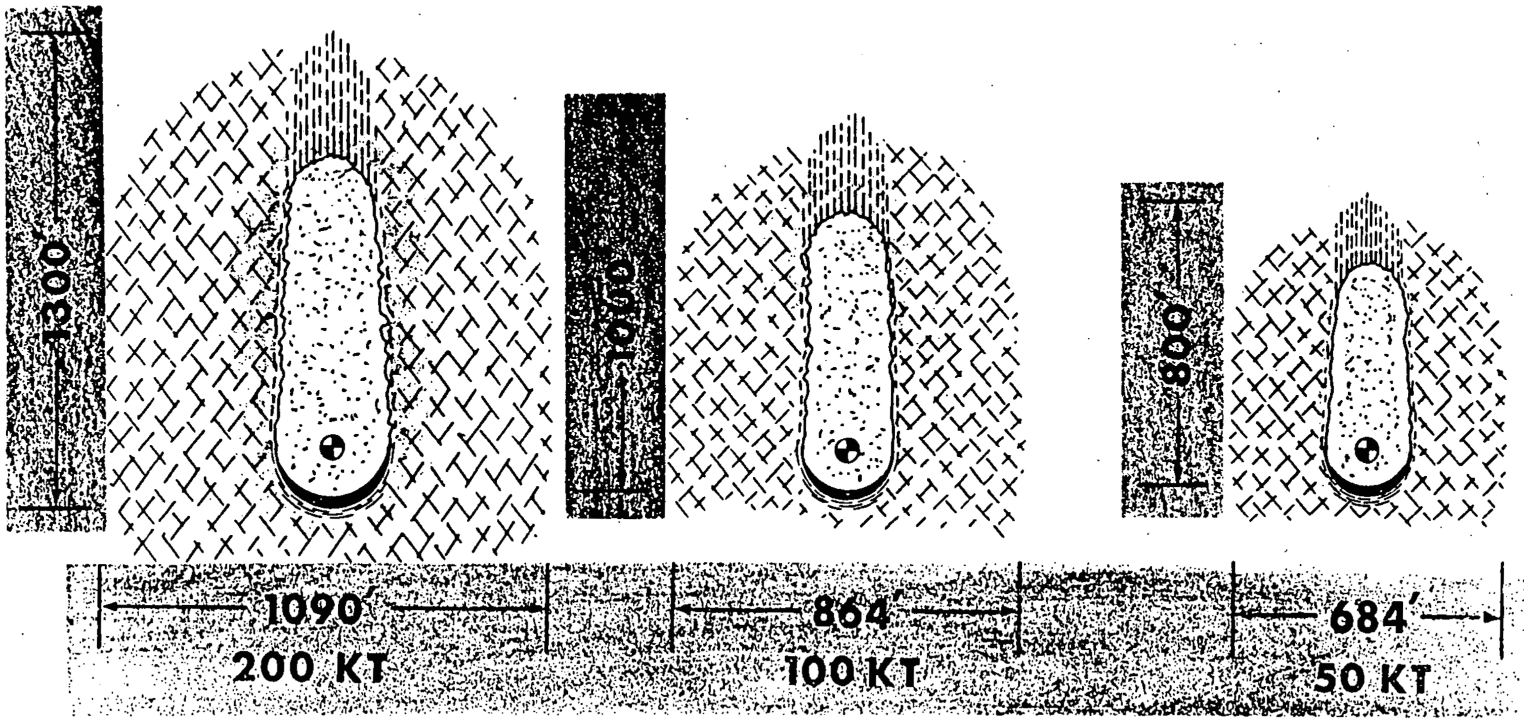
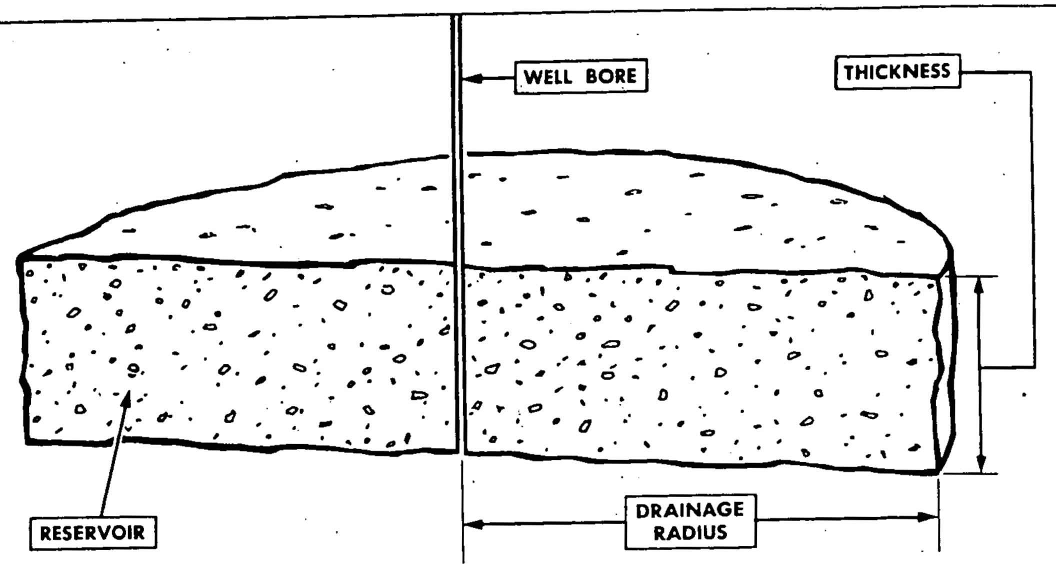


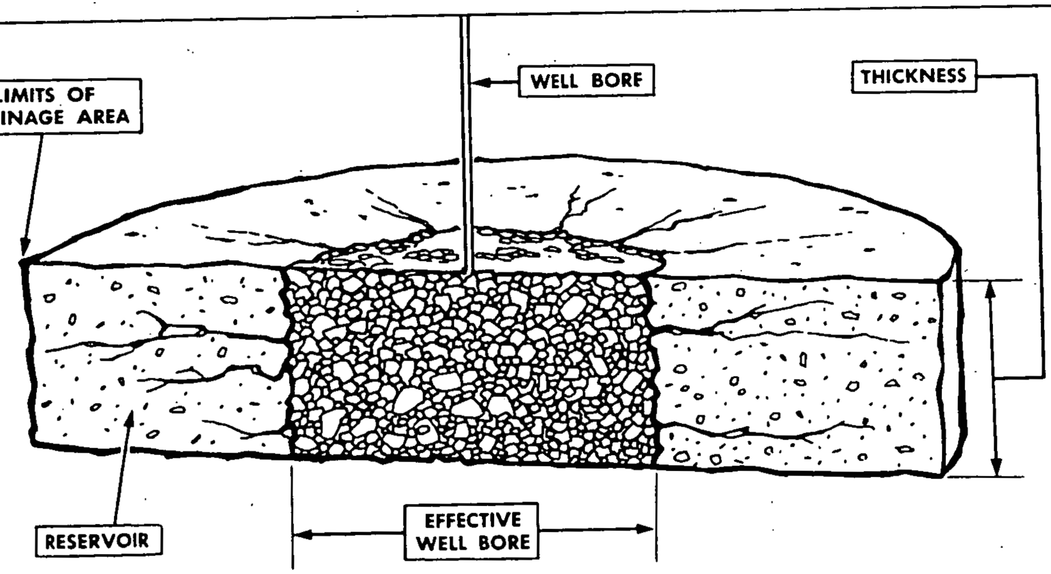
SHOT DEPTH 3000'

CHIMNEY AND BROKEN ROCK ZONES RESULTING FROM VARIOUS SIZE NUCLEAR DETONATIONS IN OIL SANDS.

Figure 1



CONVENTIONAL RESERVOIR MODEL



NUCLEAR FRACTURED RESERVOIR MODEL

Figure 2

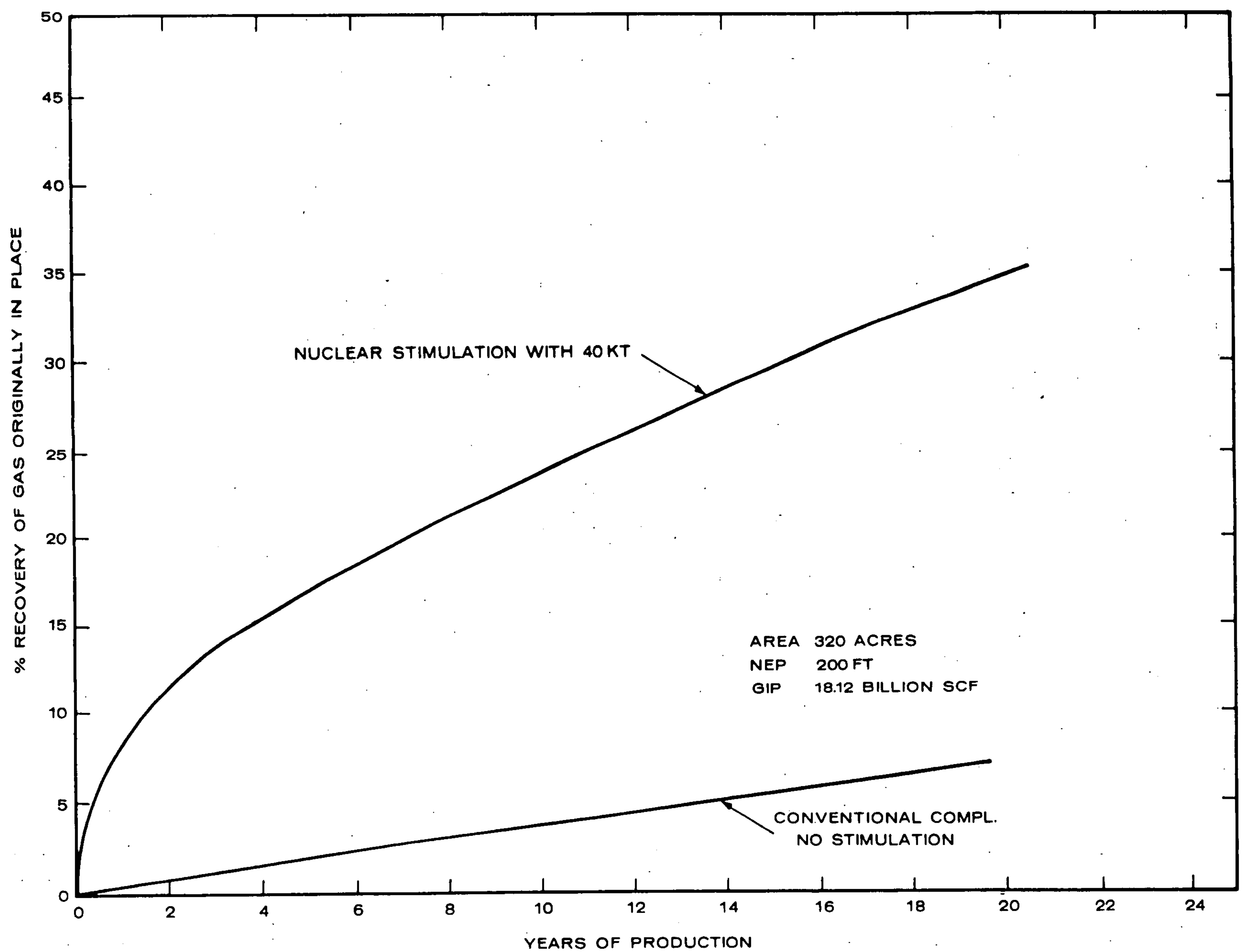


FIG. 3. EFFECT OF NUCLEAR STIMULATION ON GAS RECOVERY

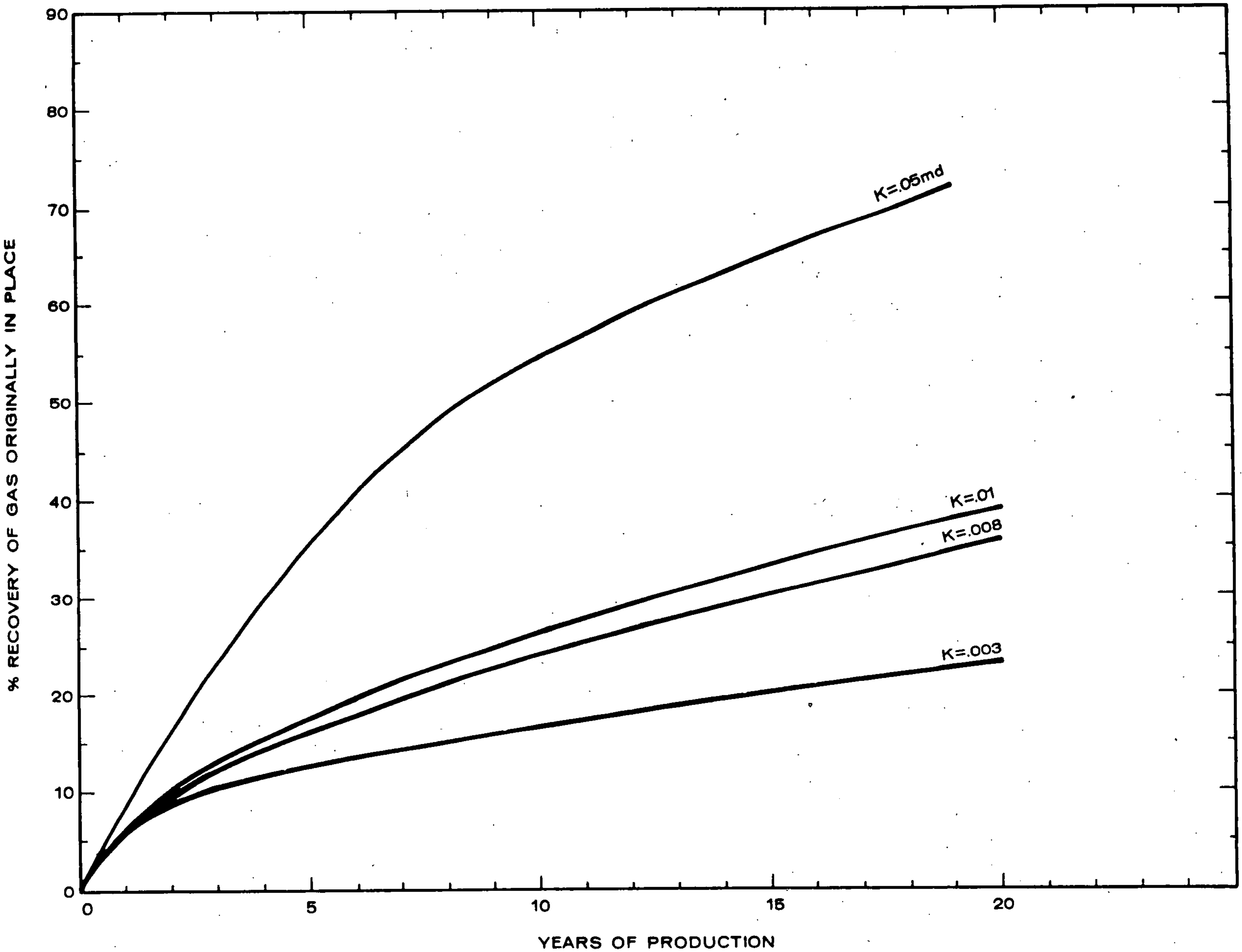


FIG. 4. EFFECT OF PERMEABILITY ON GAS RECOVERY AFTER NUCLEAR STIMULATION WITH A 40 KT DEVICE AND 320 ACRE SPACING

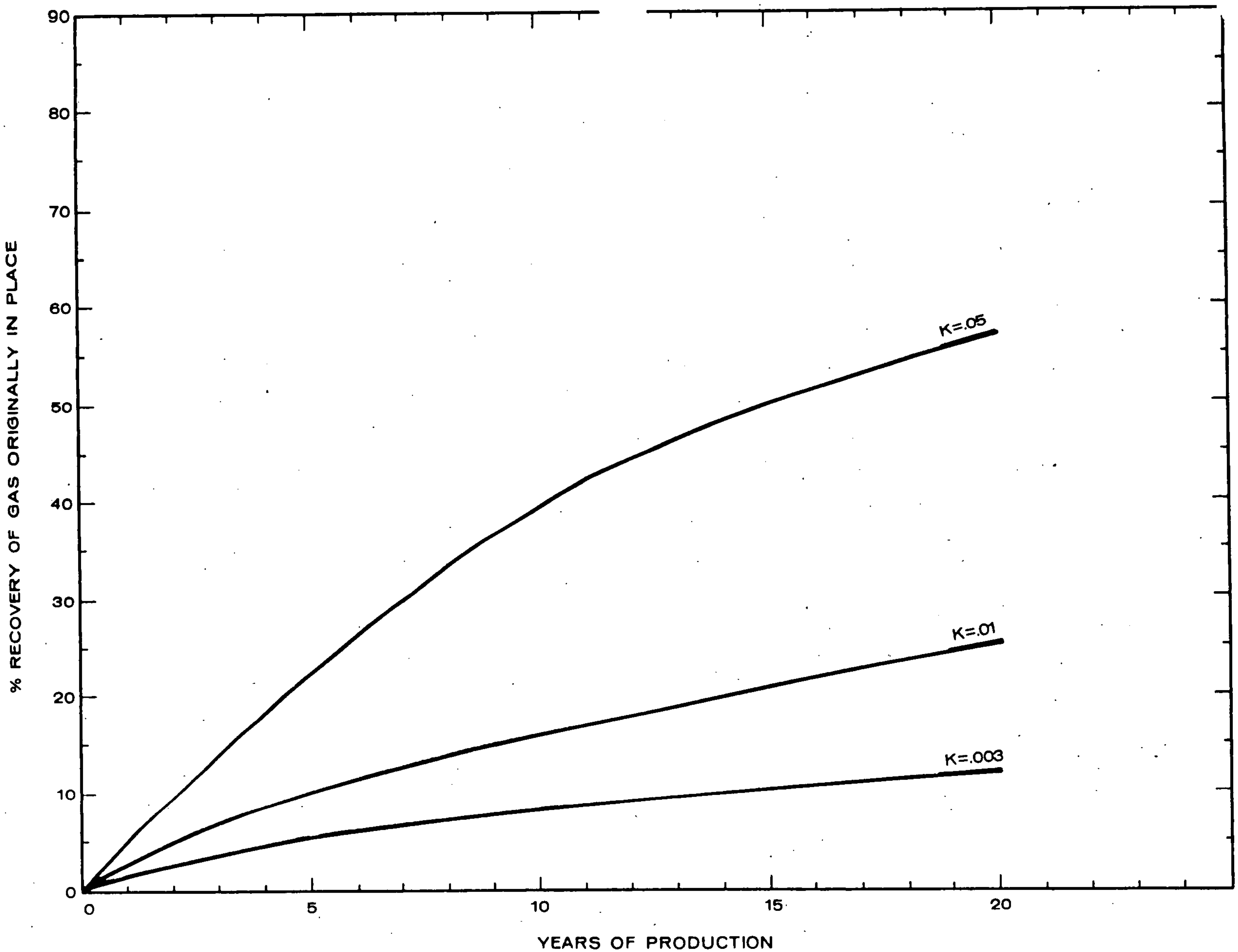


FIG. 5. EFFECT OF PERMEABILITY ON GAS RECOVERY AFTER NUCLEAR STIMULATION WITH A 5 KT DEVICE AND 320 ACRE SPACING

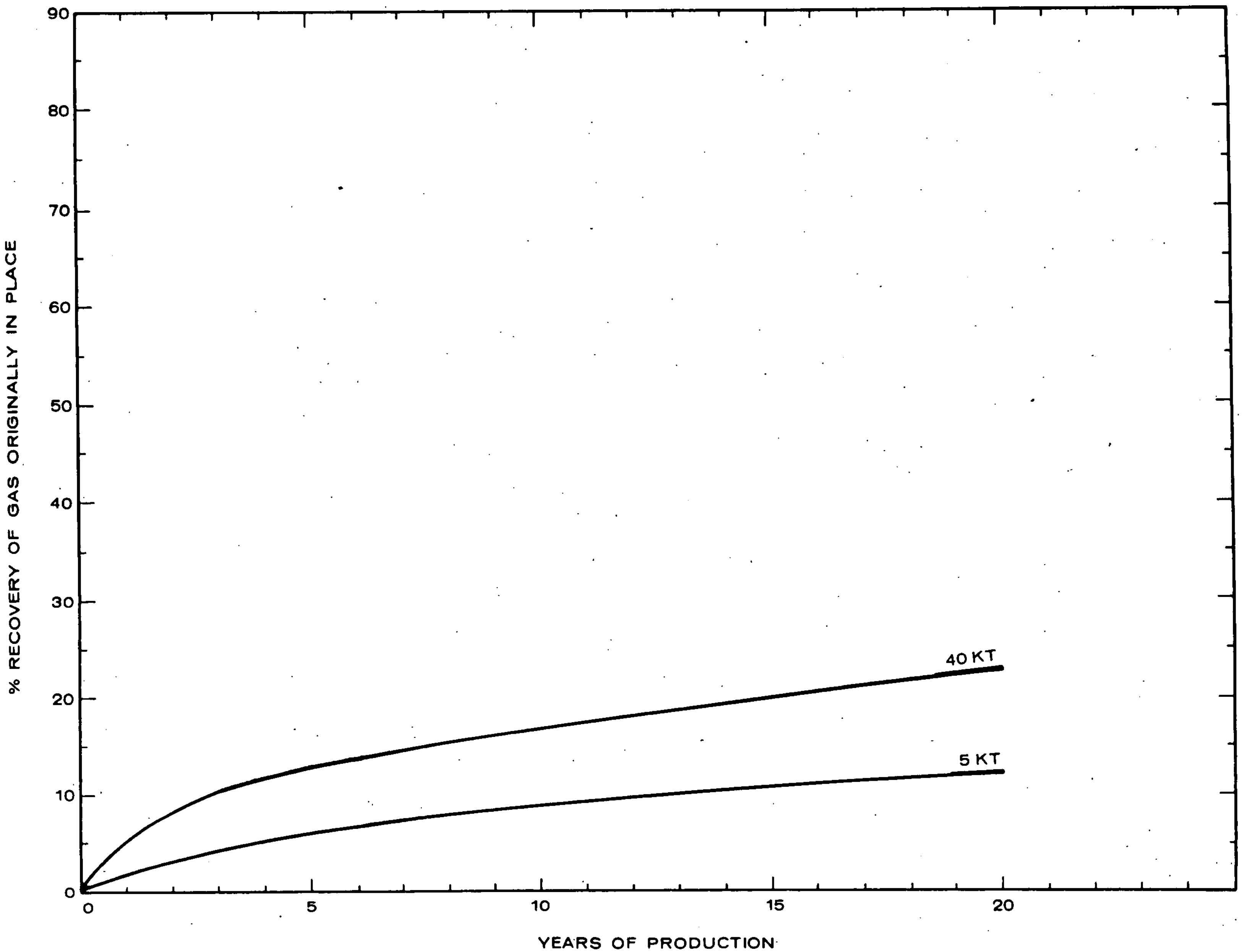


FIG. 6. EFFECT OF DEVICE SIZE ON GAS RECOVERY IN A .003 md PERMEABILITY RESERVOIR AND 320 ACRE SPACING

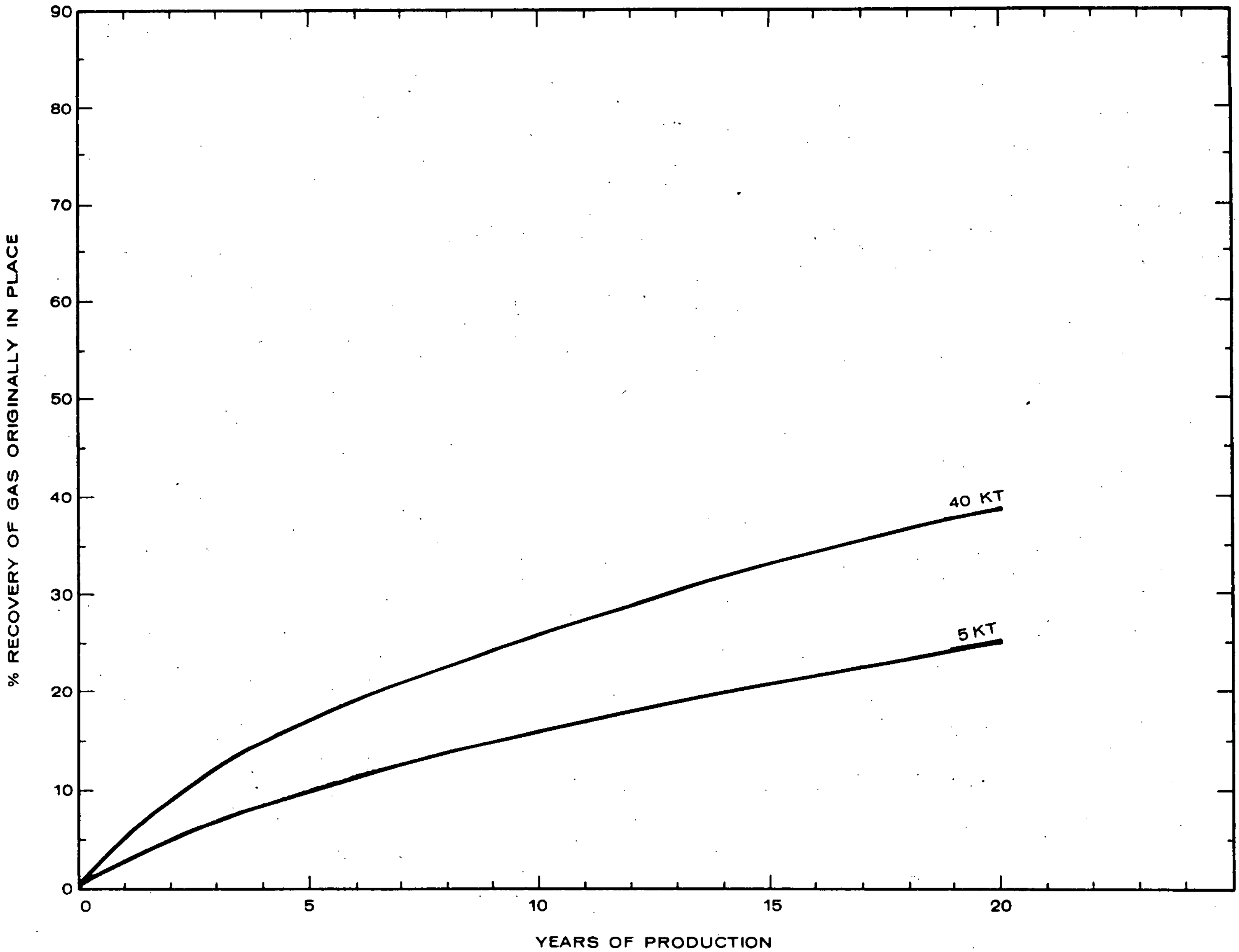


FIG. 7. EFFECT OF DEVICE SIZE ON RECOVERY IN A .01 md PERMEABILITY RESERVOIR AND 320 ACRE SPACING

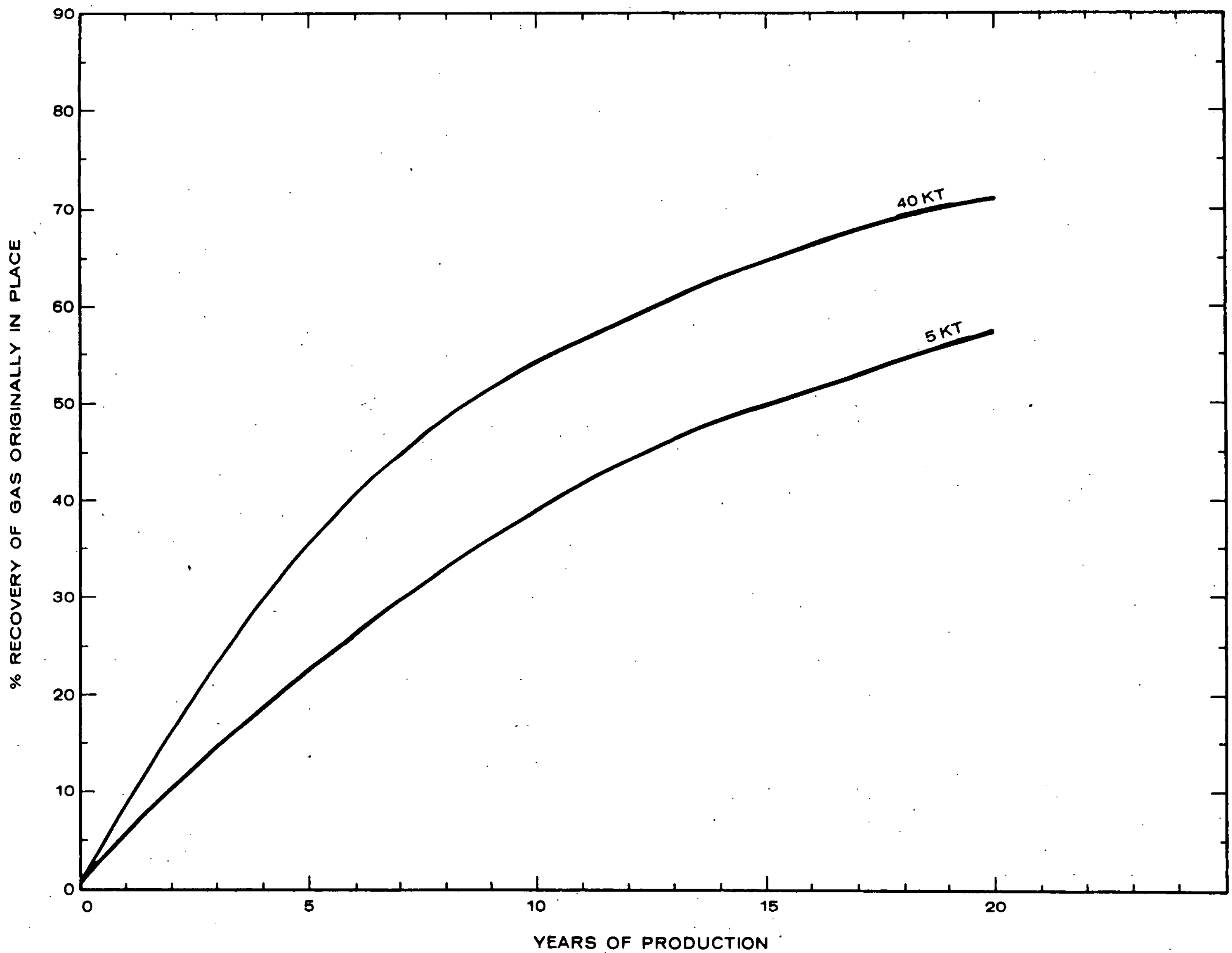


FIG. 8. EFFECT OF DEVICE SIZE ON RECOVERY IN A .05 md PERMEABILITY RESERVOIR AND 320 ACRE SPACING

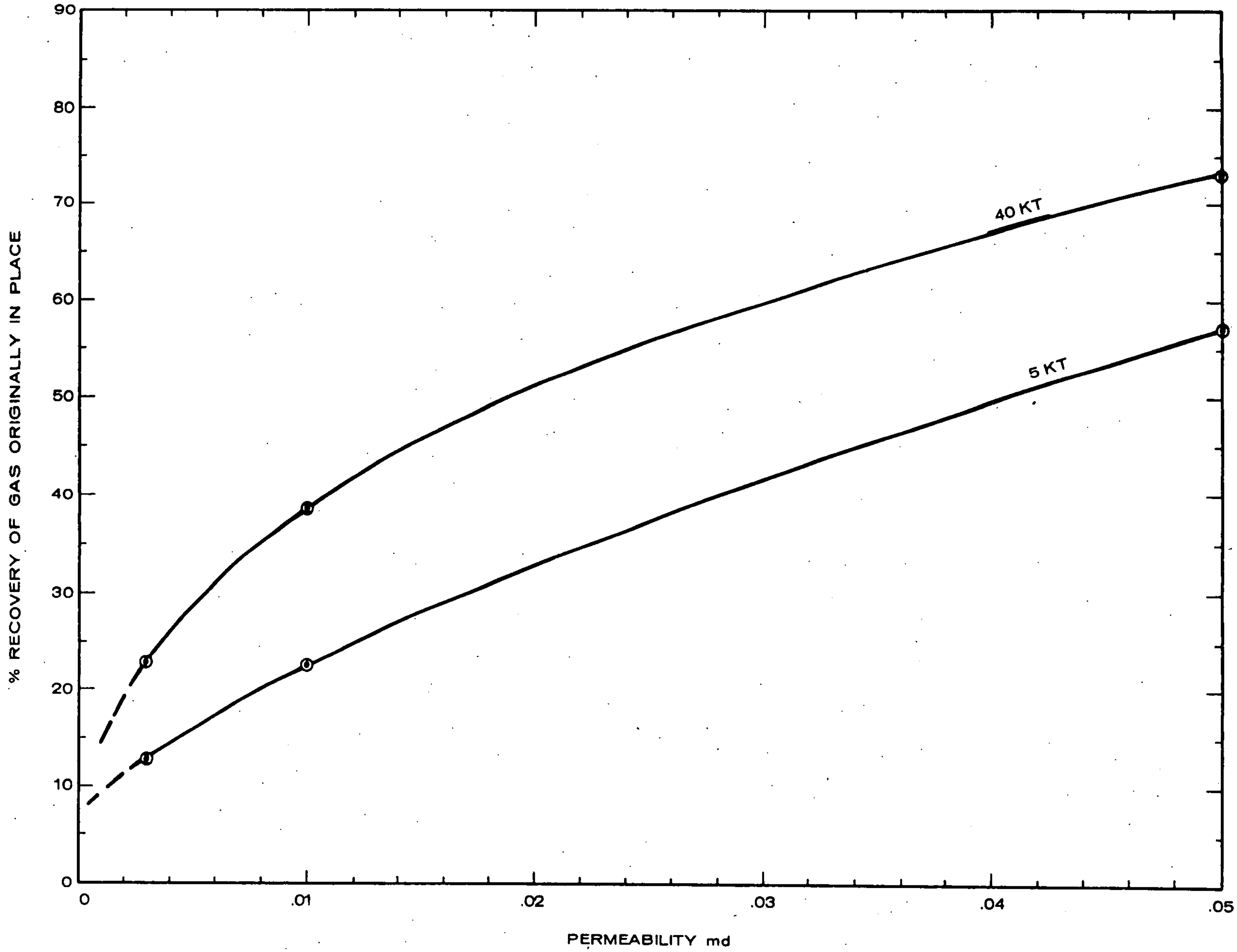
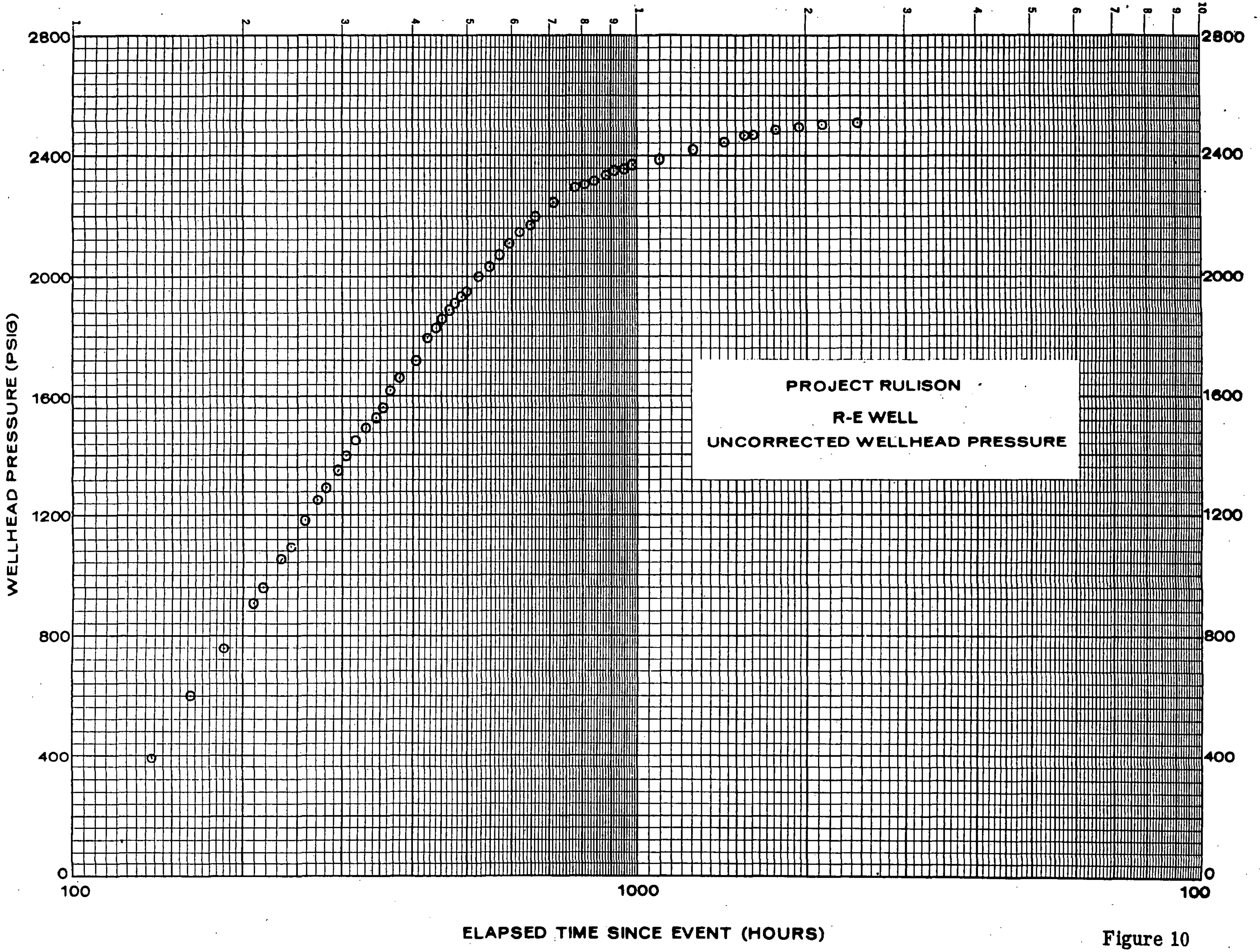


FIG. 9. EFFECT OF PERMEABILITY ON GAS RECOVERY IN 20 YEARS USING 40 KT AND 5 KT DEVICES ON 320 ACRE SPACING



PROJECT RULISON
R-E WELL
UNCORRECTED WELLHEAD PRESSURE
WELLHEAD PRESSURE (PSIG)
ELAPSED TIME SINCE EVENT (HOURS)
0
400
800
1200
1600
2000
2400
2800
100
1000
100

Figure 10

MAJOR BASINS OF ROCKY MOUNTAIN STATES

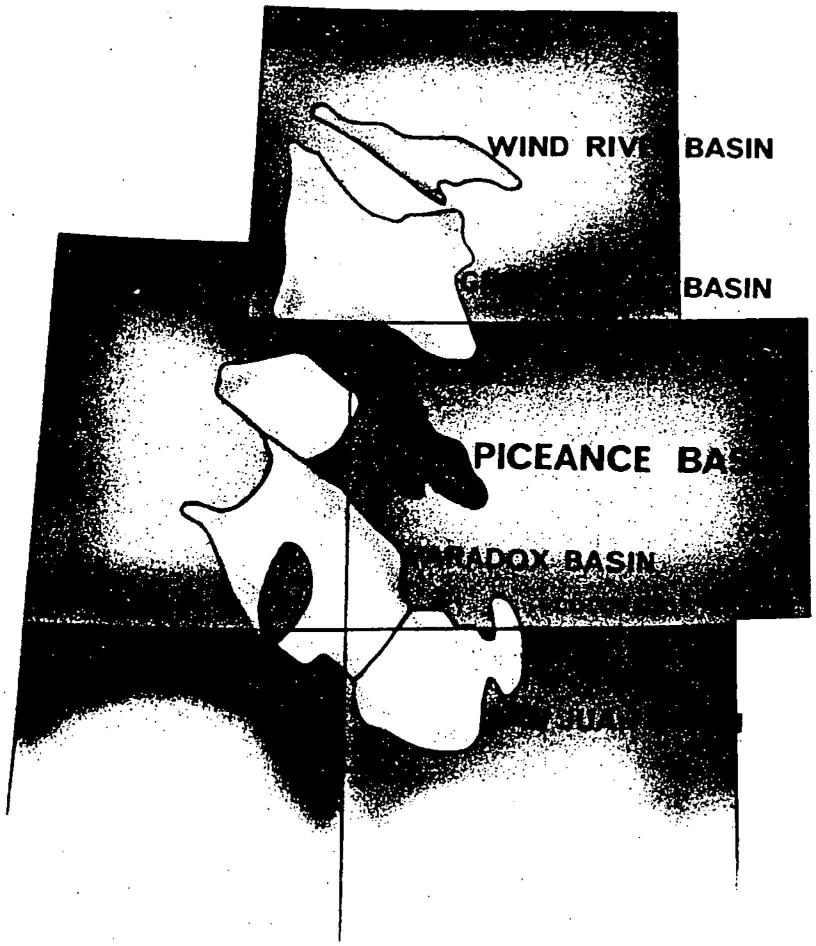
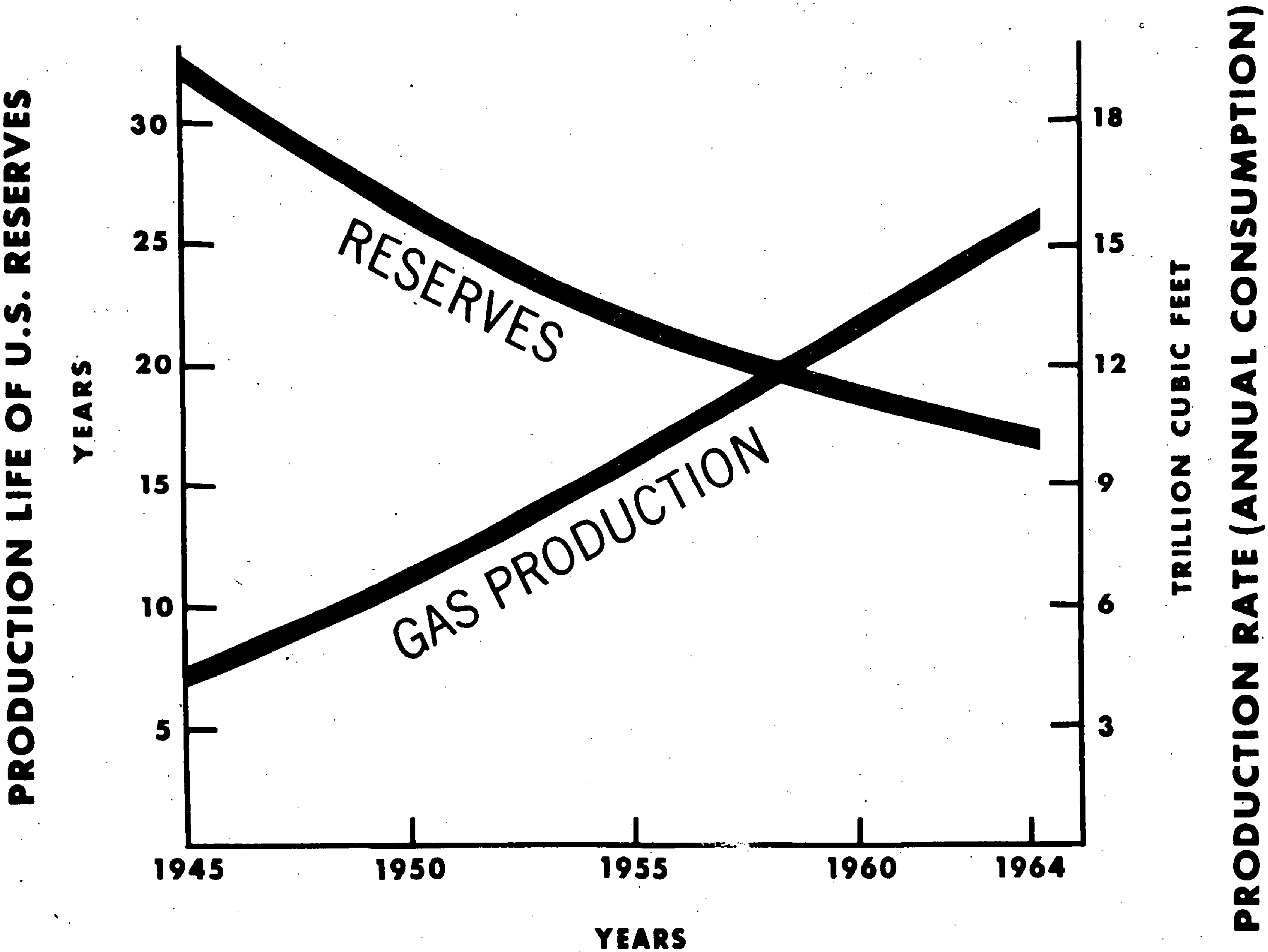


Figure 11.



NATURAL GAS AVAILABILITY IN UNITED STATES

Figure 12